Mu2e Experiment Design
The Cosmic Ray Veto

Eric L. Nguyen
University of Virginia
Spring 2011

Table of Contents

The Standard Model

Elementary Particles

Atoms are sometimes referred to as the "building blocks" of nature and the world. Indeed, the Greek philosophers such as Leucippus and Democritus thought of the atom as an indivisible reduction of matter, the remains after matter has been divided into smaller and smaller pieces until it could no longer be split. Atom literally translates into "without division" (Walker 1035), but this is a misnomer. Atoms are not "fundamental;" they can be divided into further particles (Particle Data Group). The study of these elementary subatomic particles and their interactions is the focus of particle physics. With further understanding of particle physics and microscopic nature of matter come the abundance of opportunities for discovery through which man can develop a better realization of the history and future of the universe.

The Standard Model of particle physics uses elementary particles as the fundamental building blocks of all matter. In the atom, the electron (e^-) is elementary, or fundamental. Atoms consist of a dense, positively charged nucleus and a cloud of negative electrons. The nucleus is made up of proton and neutrons. Protons and neutrons are not elementary, since they are actually composed of smaller particles called quarks (Walker 1099 and Particle Data Group). The modern atomic model can be seen in Figure 1. Quarks, leptons, and gauge bosons are elementary particles (Gribbin). The Standard Model of Elementary Particles can be seen in Figure 2. Up until the 1950s, the only known elementary particles were the Generation I particles. Through scattering experiments, many more particles added to the Standard Model of particle physics, including the muon (Group). The focus of the Mu2e experiment is the muon (μ) and electron, both of which are types of leptons (Particle Data Group).

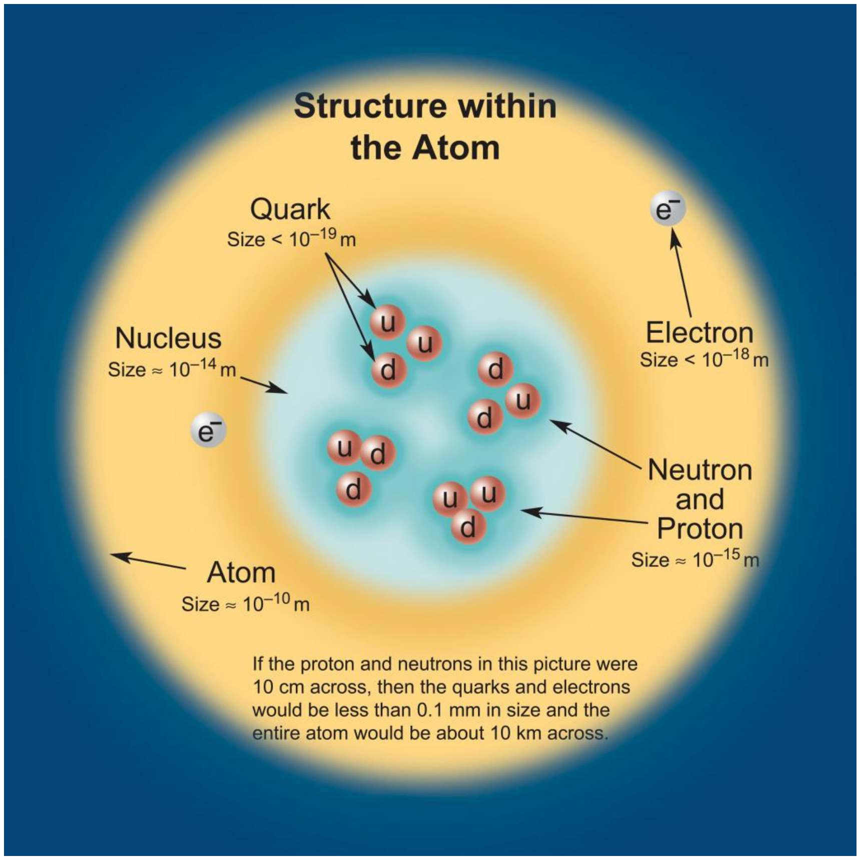


Figure 1: Modern Atomic Model
(Credit: Contemporary Physics Education Project)

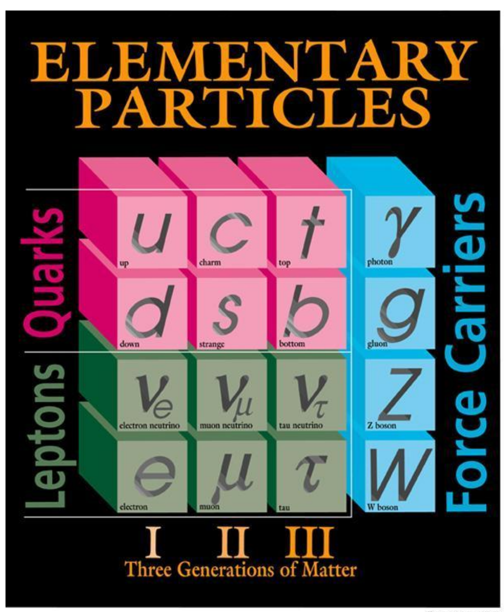


Figure 2: Standard Model of Elementary Particles
(Credit: DOE/Fermi National Accelerator Laboratory)

Particles can be categorized according to which of the four fundamental forces of nature they experience. In order of diminishing strength, these are the strong nuclear force, electromagnetic force, weak nuclear force, and gravitational force. All objects of finite mass experience gravity; objects with finite charge experience the electromagnetic forces; flavor change interactions involve weak forces; color charge interactions involve strong forces (Walker 1099 and CPEP).

Leptons are not subject to strong interactions. There are 6 types known to exist, 3 electrically charged and 3 not, all of which are elementary particles (Walker 1999 and Particle Data Group). The electron, muon, and tau (τ) particles (and their antiparticles) are charged, but neutrinos (ν) are not. Each charged lepton has a "partner neutrino." The muon and tau tend to be heavier than electrons, and the neutrinos tend to have very little mass (Particle Data Group).

The Experiment

Muon Decay

The purpose of the Mu2e (muon-to-electron) experiment is to look for a muon that does not follow the traditional weak-force decay pattern. When the muon was first discovered, physicists suspected that what was essentially a heavy electron would decay directly into an electron. Physicists have been looking for such a decay ever since, that is, mixing among the family of charged leptons (Group). Instead, due to conservation of lepton number, the muon follows a three-particle decay pattern. In the Standard Model, the muon decays to form an electron or positron, one electron neutrino, and one muon neutrino or antineutrino (Nave). While a direct muon-to-electron conversion is predicted to be not present at a detectable rate in the

Standard Model, it is possible that the process exists as an extremely rare decay. The high intensity accelerator at Fermilab will be able to observe muon decay in vast quantities, around 10^{18} muons. If found, the study of a direct muon-to-electron conversion would help physicists better understand the force interactions which cause particles in the same family to decay from heavy to lighter, more stable, mass states. This would lead to further insight into theories beyond the Standard Model, such as Grand Unification (Fermilab).

The Grand Unified Theory is a theoretical model which merges the electromagnetic, weak, and strong interactions into a single unknown force (Ross). Physicists theorize that this force was the only force present during the particle interactions immediately following the Big Bang. Many Grand Unified Theories predict that direct muon-to-electron conversion should occur at a rate detectable by the Mu2e experiment; therefore the discovery of a direct muon-to-electron conversion could be a sign of the existence of this single, grand unification of forces (Fermilab).

Particle Accelerators

The basic premise of particle accelerators can be easily understood using a relatively simple and well-known example: Rutherford's gold foil experiment. During his experiment, Ernest Rutherford shot a beam of alpha particles at a sheet of very thin gold foil, which was surrounded by a circular sheet of zinc sulfide. Rather than simply passing straight through the gold foil, some of the atoms were deflected at large angles to the foil. The paths of the alpha particles were tracked with the marks left on the zinc sulfide. By observing the path nature of the alpha particles, Rutherford was able to determine the existence of a small, dense, positively charged nucleus within the atom's structure. In "particle accelerator terms," the alpha particles made up the beam, the gold foil was the target, and the zinc sulfide screen was the detector. (Particle Data Group).

The fundamental principles behind the particle accelerator at Fermilab are similar: a proton beam from the Fermilab accelerator strikes a target surrounded by a detector. The layout can be seen in Figure 3.

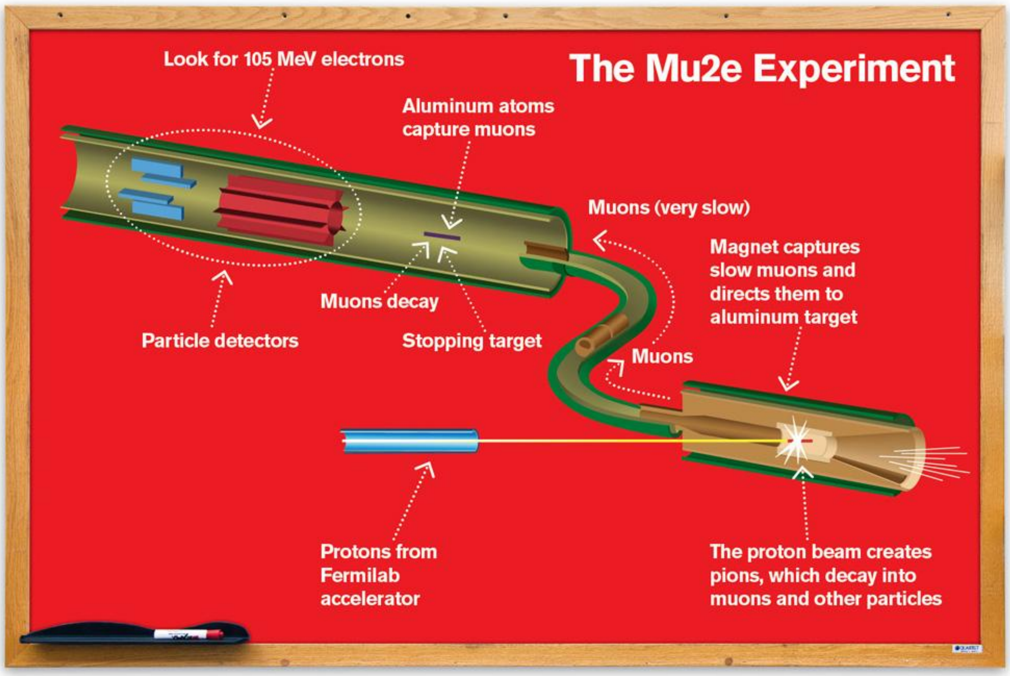


Figure 3: The Mu2e Detector Setup
(Credit: symmetry magazine)

All particles have wave properties. Waves can be reflected by a target and into a detector. For example, light waves reflect off of objects and into our eyes; sound waves reflect into our ears. Generally, smaller wavelengths allow for better resolution. Thus, in order to see small particles, the particles' wavelength also needs to be small. Since a particle's momentum and wavelength are inversely related, particle accelerators increase the momentum of probing particles to near the speed of light (Particle Data Group). In the Mu2e experiment, accelerated proton particles with very short wavelengths are collided with the water-coooled aluminum production target. As seen in Figure 3, the collision creates many particles, including pions. The pions in turn decay into muons and many other particles. This occurs in the production solenoid seen on the bottom right of Figure 3. About a quarter of a percent of the protons that hit the target produce muons that stop in the target walls (about 50 billion muons per second). The graded magnetic field in the production solenoid reverse the direction of these muons and spiral them into the transport solenoid. The muons, along with other particles, then enter an evacuated vessel. The muons still need to be further "sorted out" from the many other particles in order to observe muon decays. The curved nature of the transport solenoid helps remove extraneous particles, and muons can further be identified via their momentum and lifetime. The experiment "waits" for the lifetime of the muon so that, in theory, only muon decay is observed. A magnetic spectrometer in the detector measures particle momentum, and an electric calorimeter records particle interactions and momentum measurements too (Fermilab and Mu2e Proposal). Unfortunately, cosmic rays can create electron backgrounds through in the solenoid materials and from muon decay-in-flight. These backgrounds can be made negligible with the use of passive and active shielding systems. Heavy shielding blocks provide the passive shielding, while the Cosmic Ray Veto (CRV) system provides active shielding.

Cosmic Ray Veto

Cosmit rays muons can cause undesirable backgrounds during the experiment. The goal of the CRV is to identify and veto muons that cannot be attenuated via passive shielding. The veto system has a goal of 99% coverage and an efficiency of 99.99% (Mu2e Proposal).

The CRV is still being designed, but a general layout of the CRV around the end solenoid can be seen in Figure 4.

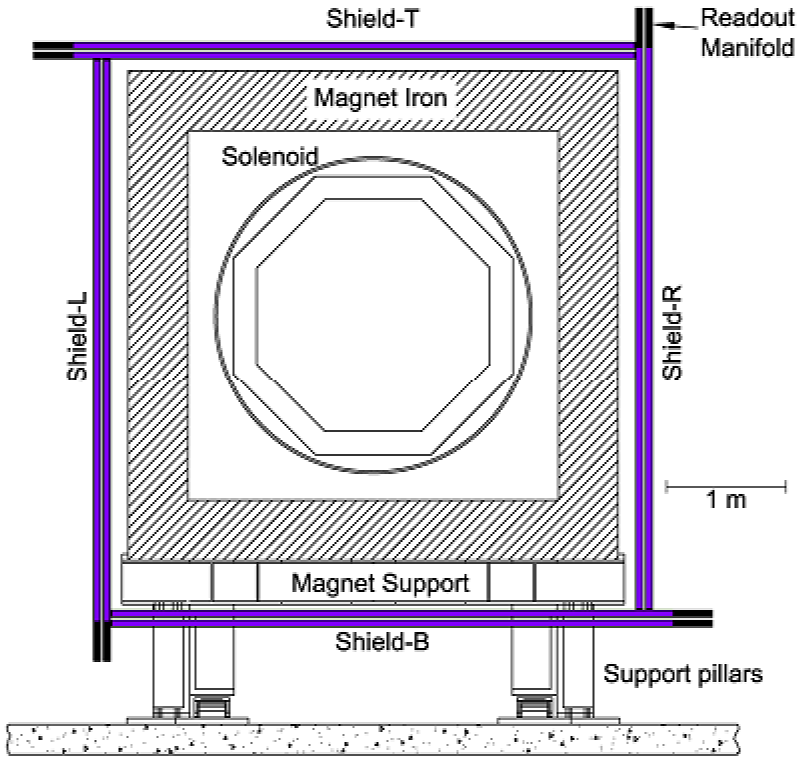


Figure 4: Orthogonal front view of the CRV
(Credit: Cosmic Ray Veto Proposal)

Each side of the CRV will be made up of 3 layers scintillator modules, overlapped in a staggered fashion. Scintillators are luminescent materials that, when struck by incoming particles, absorb the particles' energy and reemit it in the form of light (Leo). The scintillators are embedded with waveshifting fibers (WLS) which connect to some sort of electronic light detector system, such as a photomultiplier tube or SiPM array. The electronic readout allows the cosmic ray background to be measured and estimated, even when the beam is not active (Mu2e proposal). The scintillators can be seen in Figures 5 and 6.

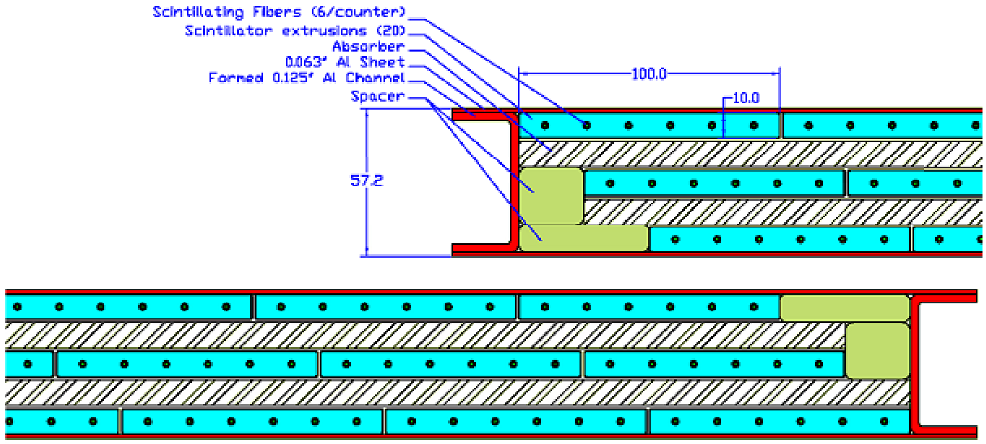


Figure 5: End view of two scintillator modules. Units are in mm.
(Credit: Cosmic Ray Veto Proposal)

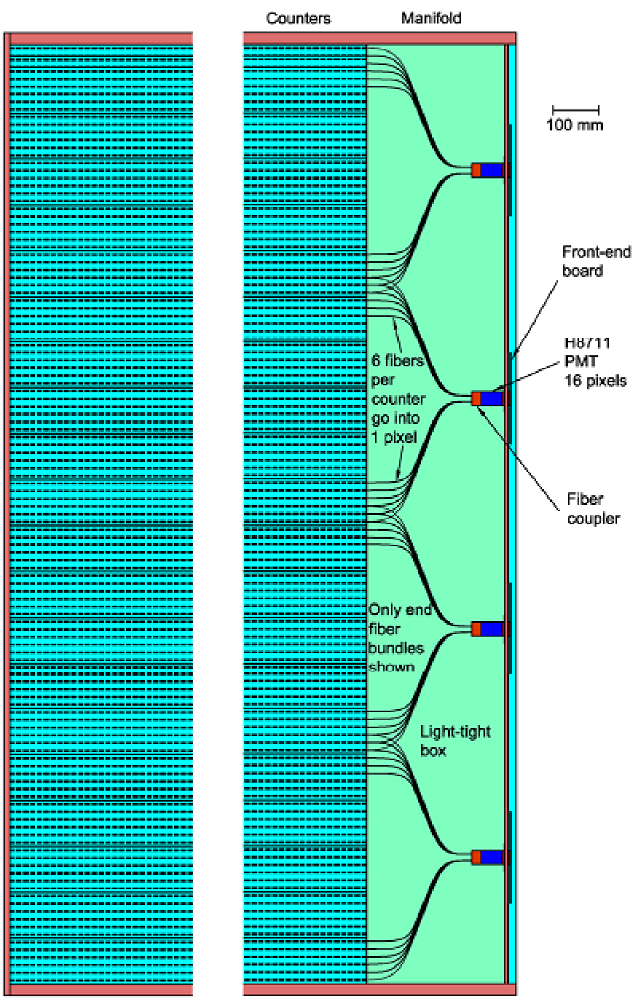


Figure 6: Front view of full sized scintillator module with connecting WLS fibers and counter
(Credit: Cosmic Ray Veto Proposal)

Various CRV Projects

As of Spring 2011, work on the CRV is still somewhat in the design stages. Particular details, such as the number of fibers per scintallator module and the electronics system, are subject to change. Over the course of the semester, several small projects were researched and developed.

Round Room

The baseline design for the CRV is from William & Mary. As such, the College had their own fabrication building floor plan. In order for scintillators to be modeled, built, and designed locally in the University of Virginia's High Energy Physics (HEP) building, the floor plan from William & Mary had to be rearranged so that the components would fit in the HEP's building's upper floor, dubbed the "Round Room." It is also important that the components are placed logically for module assembly and shipping.

Below is the original William & Mary floor plan (Figure 6).

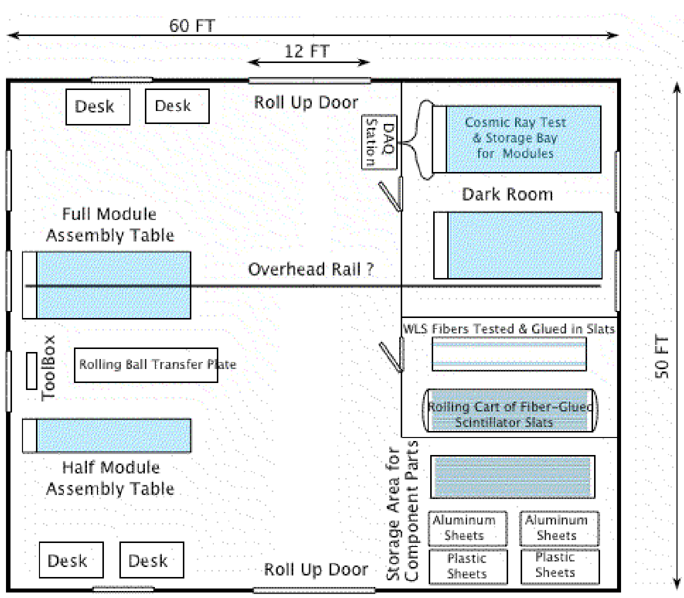


Figure 6: William & Mary fabrication building floor plan
(Credit: William and Mary)

The AutoCAD drawing for the HEP's floor plan was scaled according to William & Mary's floor plan (Figure 7). A ceiling crane is available in the HEP to move module components from station to station.

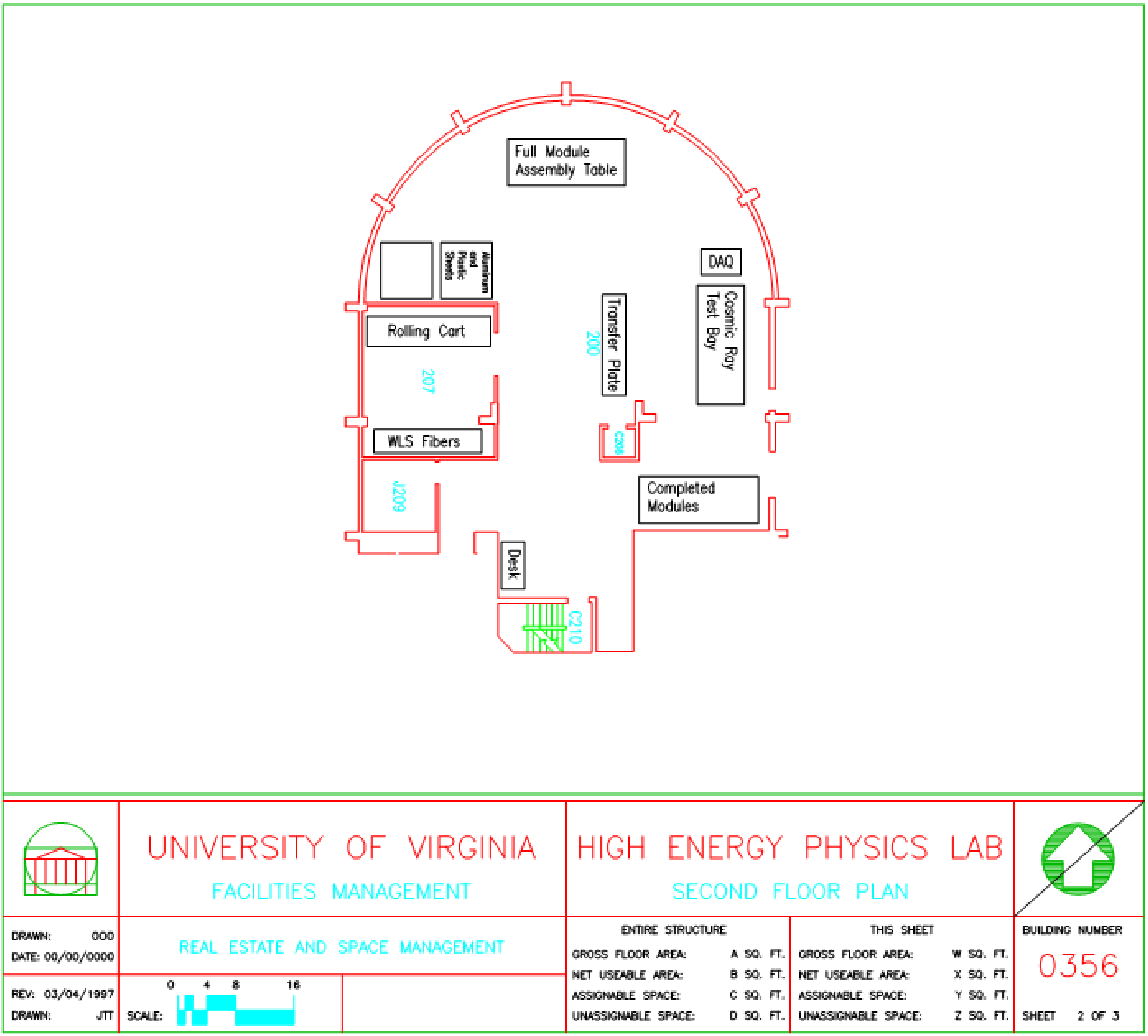


Figure 7: HEP Round Room Layout

Photomultiplier Tubes

The current design connects photomultiplier tubes (PMT) to the WLS fibers; these act as light detectors. While relatively simple to implement, there are several disadvantages to PMTs.

One problem is "cross-talk." As seen in the figure below, the fiber-input face of the PMT is arranged in a cross-grid pattern (Figure 8).

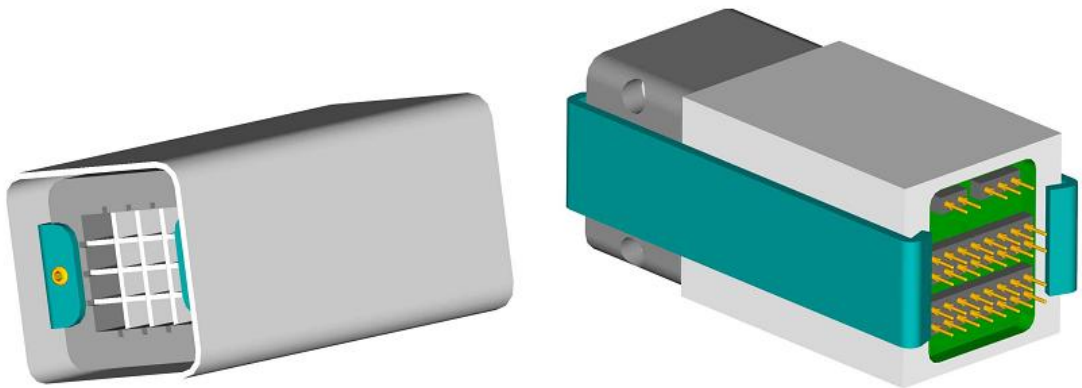


Figure 8: Isometric views of the PMT design

Since cosmic rays penetrate the 3 layers of the scintillator module and trigger a light detection, it is important that the fiber connections are arranged properly so that the PMT triggers caused by light leakage in the cross-grid are not accidently interpreted as cosmic rays. This is best explained with a diagram (Figure 9).

Black = Scintillator # (Left)
Red = Pixel # / Amp # (Right)

Black=Scintillator# (Right)
Blue=Pixel # / Amp # (Left)

1 / 10	2 / 9	3 / 16	4 / 15	5 / 14	6 / 9	7 / 5	8 / 1	9 / 14	10 / 10
11 / 7	12 / 6	13 / 5	14 / 12	15 / 11	16 / 6	17 / 2	18 / 15	19 / 11	20 / 7
21 / 4	22 / 3	23 / 2	24 / 1	25 / 8	26 / 3	27 / 16	28 / 12	29 / 8	30 / 4

(view from readout end)

View from back of the guide block (inside detector)

PMT Pixel # (Left)

	9	5	1
14	10	6	2
15	11	7	3
16	12	8	4

Empty box = no fiber

PMT Pixel # (Right)

16	12	8	4
15	11	7	3
14	10	6	2
	9	5	1

View from back of the guide block (inside detector)

Amp Card Channel # Left									Amp Card Channel # Right
	9	11	13	15	15	13	11	9	
	1	3	5	7	7	5	3	1	
	10	12	14	16	16	14	12	10	
	2	4	6	8	8	6	4	2	

Figure 9: Scintillator Mapping

Notice how the on the left, the scintillator numbers (black) 1, 11, and 21 are vertically adjacent. Therefore, the PMT connecting pixels, (red) numbers 10, 7, and 4 are intentionally placed neither directly vertical nor horizontal of each other on the PMT cross-grid. Otherwise, cross-talk between those numbers may cause confusion as to whether or not a cosmic ray caused light detection.

Additionally, the PMTs are sensitive to magnetic fields and require magnetic shielding. As discussed, the solenoids require magnetic fields for operation, which happen to be quite large. This may influence the feasibility of the use of PMTs. However, some companies, such as Hamatsu, offer magnetic shield cases designed for PMTs. Shielded PMTs are more likely to achieve a stable output than unshielded PMTs. The E989 series uses a permalloy that his an extremely high permeability of about 1e5. The shielding factor can range from 1/1000 to 1/10000. This means that the magnetic field intensity within the casing can be attenuated from 1/1000 to 1/10000 of the field intensity outside of the shield case (Hamatsu).

SiPM Research and Modeling

SiPMs, or silicon photomultipliers, could act an alternative to PMTs. These are single photon counting devices, which typically combine many small pixels into a matrix for higher dynamic range and resolution. They are compact, have high gain, and consume little power (<40µW per mm^2) (Otte). Perhaps most importantly, they are insensitive to magnetic fields. Below is a picture of a SiPM's sensitive area are SiPM package, respectively (Figure 10).

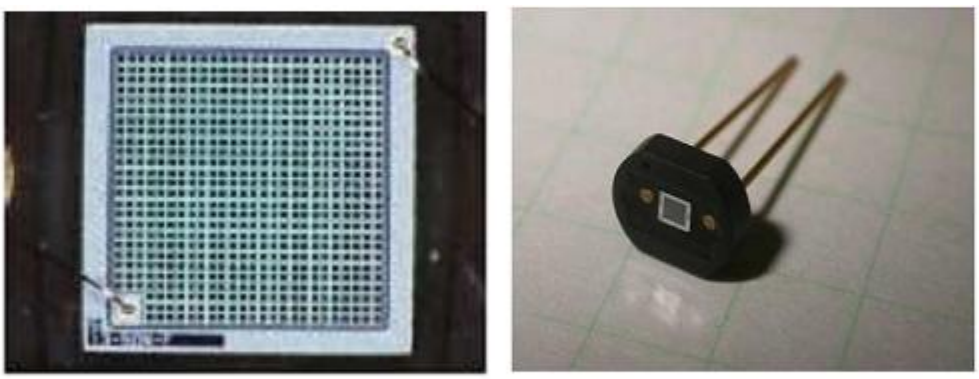


Figure 10: SiPM sensitive area (left) and SiPM ceramic package (right)
Credit: (Vacheret, et. al.)

Each fiber would connect to a single SiPM, thus some sort of SiPM array would have to be built. The SiPMs would attach to a board with some sort of "cookie" to hold them in place. The cookie would simply be a grid with holes that circumscribe each SiPM package for secure placement. A second cookie with a smaller diameter, that is, the about the diameter of the WLS fiber, would be placed on top of the first cookie. This would help with fiber alignment. Theoretical mock-ups of this design have been modeled in AutoCAD inventor. They are presented on the following page (Figure 11 and 12).

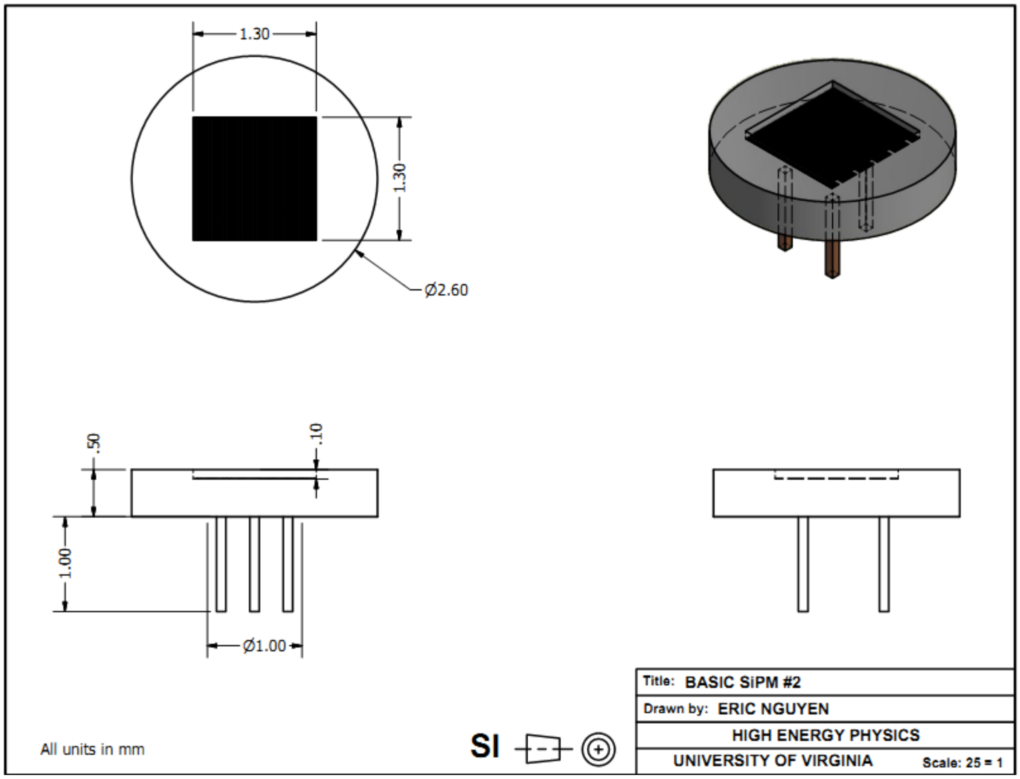
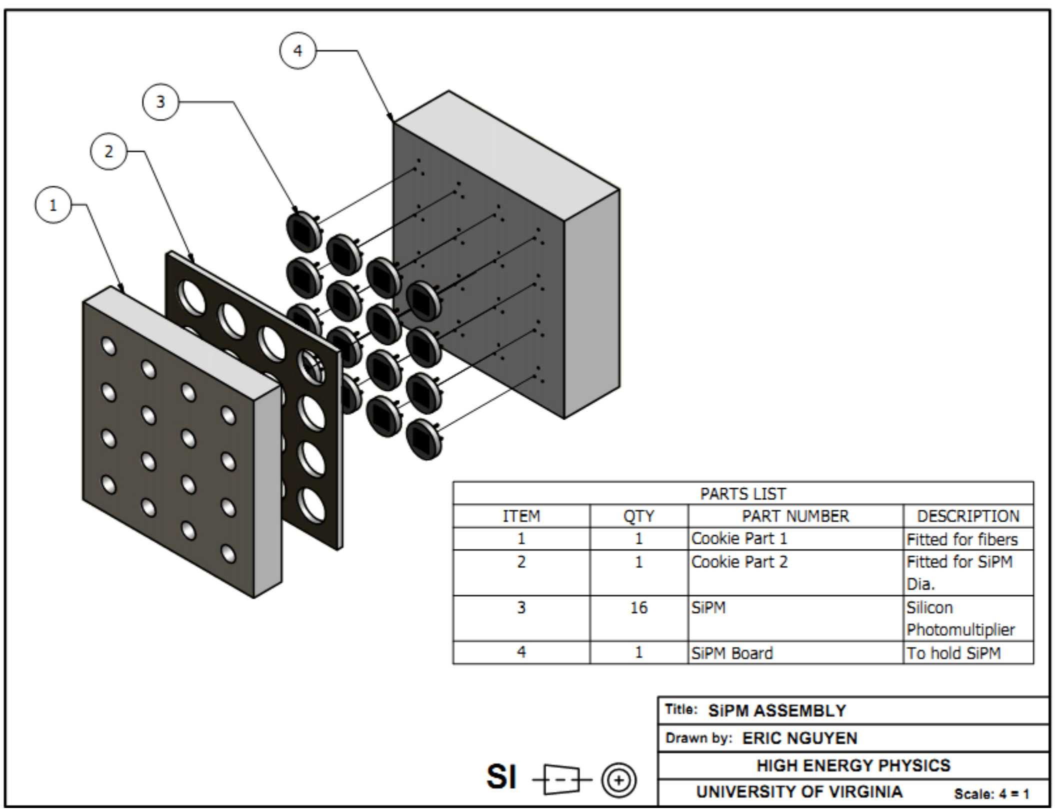


Figure 11: Model of SiPM package



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Cookie Part 1	Fitted for fibers
2	1	Cookie Part 2	Fitted for SiPM Dia.
3	16	SiPM	Silicon Photomultiplier
4	1	SiPM Board	To hold SiPM

Figure 12: Model of SiPMs in board with cookies

Of course, there are disadvantages to using SiPMs too. For instance, SiPMs have much less noise when cooled. The figure below graphically demonstrates the increase of dark noise rates with higher temperatures of operation (Figure 13). The data is from a separate collaborative study on SiPMs. The interpretation and data reduction is directly from said study.

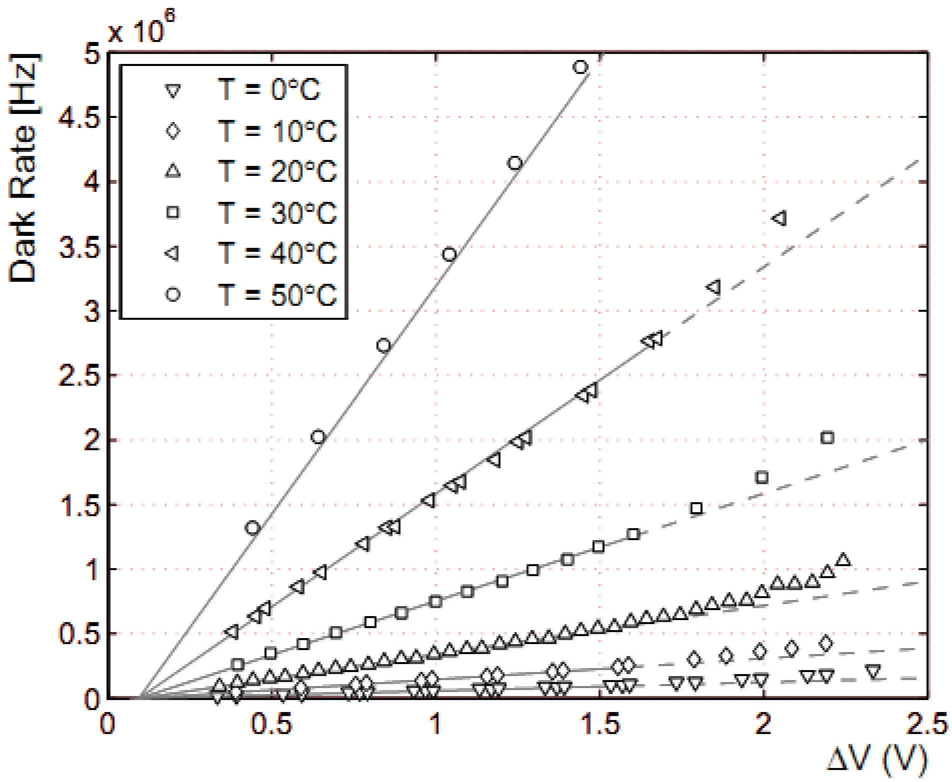


Figure 13: "Dark rate vs. overvoltage ΔV at different temperatures (sensor number TA 8120)"
Credit: (Vacheret, A., et. al.)

It is possible that some sort of cooling system would need to be implemented in order for the SiPM array to be used effectively. One possibility is through the thermoelectric effect, through a device known as a Peltier cooler.

Peltier Cooling

The thermoelectric effect converts temperature differences to electric voltages and vice-versa. Devices like thermocouples use this effect to measure temperatures via a voltage difference output; while devices like Peltier coolers use voltage differences to provide a temperature gradient. These devices are small, quick, non-mechanical and reliable, but they tend to be inefficient (Utz).

A graphical demonstration is shown below (Figure 14).

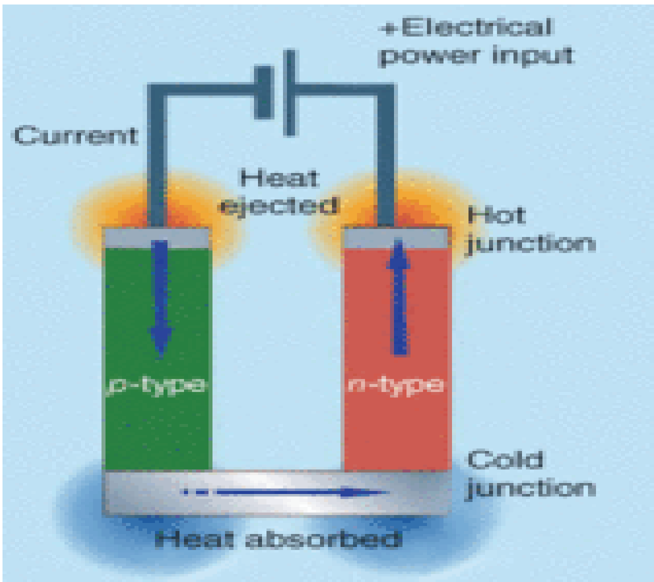


Figure 14: Peltier cooler use of the thermoelectric effect
(Credit: Utz)

N-type materials are doped too have an excess of electrons, while p-type materials are doped to have an excess of positive "holes." This affects the behavior of electron flow when power is applied (Garner).

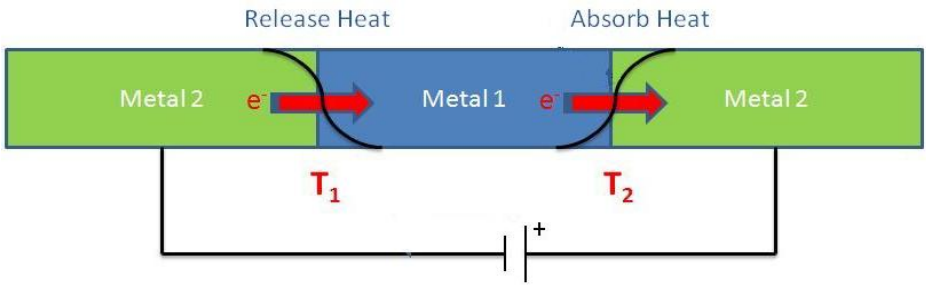


Figure 15: Peltier effect
(Credit: Utz)

An applied voltage forces electrons across the junctions. Electrons flow from Metal 2 to Metal 1 and lose energy to the metal, and electrons that flow from Metal 1 to Metal 2 absorb energy from the metal (Utz) (Figure 15).

A typical Peltier cooler is shown below. It consists of a large amount of thermocouples between two thin ceramic plates (Figure 16). A voltage can be applied in either direction to cool one side and heat the other. When the polarity is reversed, so is the direction of the temperature gradient (Steinbrecher).

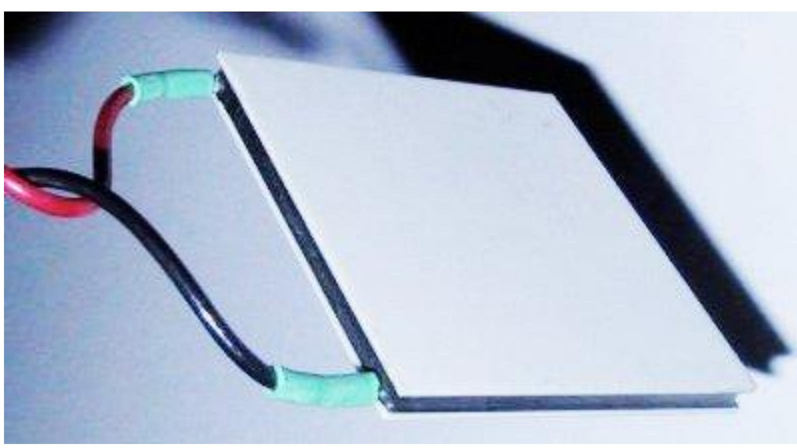


Figure 16: 40x40mm Peltier element
(Credit: Steinbrecher)

These coolers act as heat pumps. However, unlike traditional compression cycle heat pump systems, such as a refrigerator, Peltier cooler's Carnot efficiency run from only about 5-

10%. A compression cycle heat pump system can have Carnot efficiency of about 40-60% (Steinbrecher). A heat sink can be placed on the heat ejection side for effective heat transfer.

The maximum temperature difference between the hot and cold side is typically about 70 °C. This is a theoretical maximum that cannot actually be obtained, because the temperature difference is a function of the amount of heat transported; the maximum occurs only when no heat is being transported. For each temperature difference, there is a necessary amount of power that needs to be transferred in the form of heat. Additionally, as current flows through the Peltier, there is internal heating via I^2R. Manufacturers tend to have performance specifications with their coolers. An example from Tellurex is shown below (Figure 17).

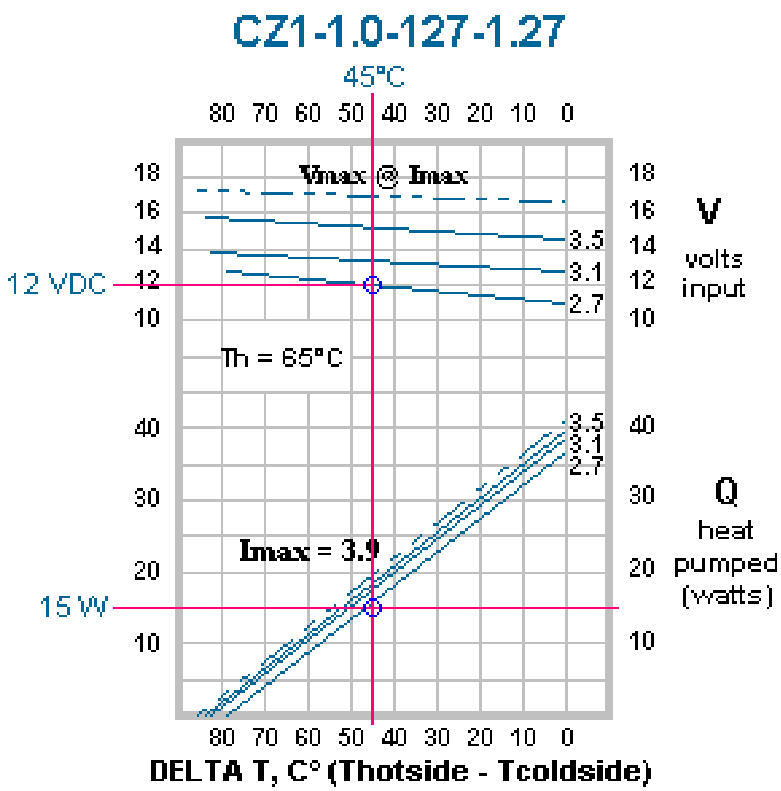


Figure 17: Peltier cooler performance curve
(Credit: Tellurex)

For easier interpretation, this curve has been simplified to a chart with a set voltage of 12 volts (Figure 18).

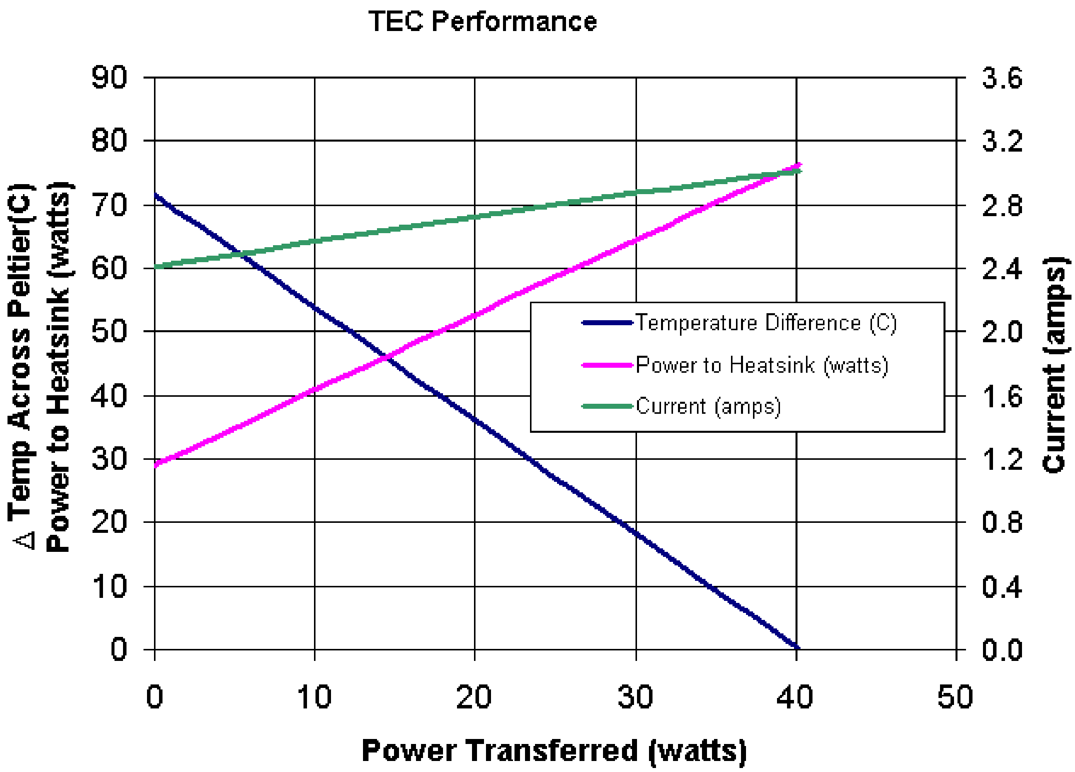


Figure 18: Performance curve at 12V
(Credit: Steinbrecher)

The left axis shows both the temperature difference and the total power to the heat sink. As an example, 15 Watts of power transfer by the Peltier cooler (horizontal axis) leads to 45 Watts of heat transferred to the heat sink. This means 30 Watts of heat is due to internal resistance (Steinbracher).

Essentially, to solve for the actual cold side temperature, one has to first find the total power output. Consider the following example, again with a curve from Tellurex (Figure 19).

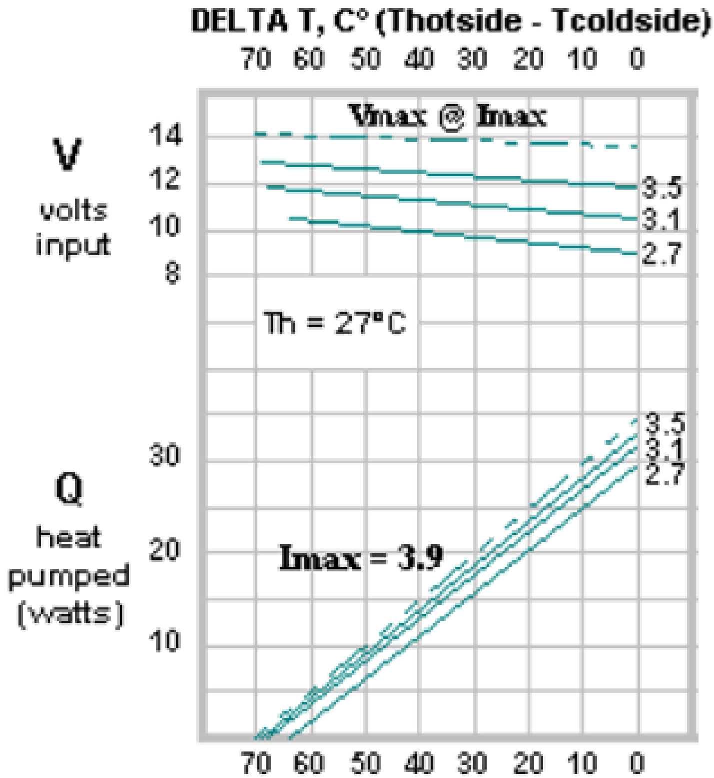


Figure 19: 27°C Tellurex Curve

At a hot side temperature of 27 °C, say the desired temperature gradient for the Peltier cooler is ΔT = 35°C. This is the difference between the hot and cold side that the Peltier cooler enforces. The temperature is not simply 27 minus 35 °C due to power generation. At an ampage of I = 2.7, the heat pumped is 13 Watts. Additionally, the curve shows that the voltage input for 2.7 amps is around 9.2 V. Power from this factor is simply 2.7 amps multiplied by 9.2 V. Thus, total power output from the thermoelectric cooler is 13 watts plus the product of 2.7 and 9.7. This is 37.84 Watts. Assume a heatsink rating of 0.5 °C/W, then the product of 0.5 and 37.84 is 18.92 °C. The total heat sink temperature would be the room temperature plus this additional temperature. Assuming the room temperature is 27 °C, the heat sink would be at 45.92 °C. Thus, since the cooler is enforcing a 35 °C gradient, the cool side would be the difference between the heat sink and 35 °C, or 10.92 °C.

Clearly, the interpretation of these graphs can become complicated. For simplification, an Excel sheet has been made to demonstrate the calculations. It can be found under "Sample Peltier Cooler Calulator.xls." The input is the set temperature gradient. The output is the cold side temperature. This calculator is only an example since the calculations depend on the Peltier cooler specifications and ampage curve used. These procedures were all derived by analyzing the work of Steinbrecher.

Conclusions

The Cosmic Ray Veto system is a vital component to the Mu2e experiment. Without it, none of the data collected during the experiment could be validated, and the goals of the Mu2e experiment could never be achieved. The explicit purpose of the Mu2e experiment is to detect a direct muon-to-electron conversion with unprecedented sensitivity. Yet the implications of testing and understanding of this expansion to the Standard Model of particle physics extend much further. The experiment could offer a perspective that would narrow down the solutions to key physical questions asked on all the frontiers of high energy physics. In essence, the experiment would aid in the understanding of the true fundamental building blocks of the universe throughout the past, present, and future. Indeed, the thirst for discovery continues throughout the entire space-time continuum and realms beyond.

Works Cited

Austell, Bryce T. *Muon-to-Electron Conversion Experiment (Mu2e) Dectector Solenoid Design*. Office of Science, Summer Internships in Science and Technology Program. 2010.

The Contemporary Physics Education Project (CPEP). http://www.cpepweb.org/cpep_sm_large.html

Dukes, Craig. *Cosmic Ray Veto Proposal*. (internal document)

Dukes, Craig. *Mu2e Proposal*. Fermilab, 2008.

Fermilab. *Mu2e: Muon-to-Electron Conversion Experiment*. 2010. http://dev.xenomedia.com:22082/

Garner, Gavin. MAE 4710 Mechatronics 2011 Lab Manual. University of Virginia

Gribbin, John (2000). *Q is for Quantum - An Encyclopedia of Particle Physics*. Simon & Schuster, 2000

Hamamtsu Japan. *Magnetic Shield Case*. http://jp.hamamatsu.com/products/sensor-etd/pd002/pd413/pd420/index_en.html

Leo, W. R. *Techniques for Nuclear and Particle Physics Experiments*. 2nd ed. New York: Springer-Verlag, 1994. Print.

Mu2e Experiment Profile. http://www.fnal.gov/pub/today/profiles/Mu2e.html

Nave, C. R. *HyperPhysics*. Georgia University Department of Physics and Astronomy, 2005.

Otte, Nepomuk. *The SiPM status on R&D in Munich*. Max-Plank-Institute for Physics Munich.

Particle Data Group. *The Particle Adventure: The Fundamentals of Matter and Force*. Berkeley Lab, 2009. http://particleadventure.org/index.html

Ross, Graham G. *Grand Unified Theories*. Boulder, CO: Westview, 1984. Print.

Steinbrecher, Tillmann. *The Heatsink Guide*. 2010. http://www.heatsink-guide.com/peltier.htm

Utz, Marcel. MAE3820/40 Thermoelectrics Lab. University of Virginia.

Vacheret, A., et. al. *Characterization and Simulation of the Response of Multi Pixel Photon Counters to Low Light Levels*.

Walker, James S. *Physics*. Third ed. Vol. II. San Francisco: Pearson, 2007. Print.